Intermediate-Scale Tests of the Gas-Phase Partitioning Tracer Method for Measuring Soil-Water Content

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ABSTRACT

Experiments were conducted in a well-instrumented weighing lysimeter (2.5 by 4 m) to evaluate the efficacy of the gas-phase-partitioning tracer method for measuring soil-water content. The method is based on the use of conservative (nonpartitioning) and water-partitioning tracers, wherein the partitioning tracer transfers into the water, which retards its movement with respect to that of the nonpartitioning tracer. This retardation is a function of the soil-water content. The volumetric soil-water contents estimated from comparative moment analysis of the measured breakthrough curves were compared with values obtained using traditional methods, including gravimetric core analysis, neutron thermalization, time domain reflectometry, and conversion of soil tension. The values obtained from the tracer tests compare favorably with the independently determined values. For the lower soil-water contents (6-7%), the tracer-estimated values were \approx 98% of the measured values. For the higher soil-water content (15%), the tracer estimated values were \approx 77% of the measured values. These results indicate that the gas-phase partitioning tracer method can provide representative estimates of soil-water content under the relatively ideal conditions employed herein.

THE MAJORITY of the methods in current use for measuring soil-water content provide what can be considered as point values of soil-water content due to their relatively small sample volumes (10^{-1} -m scale). While this is an advantage for obtaining accurate information at small scales, it is a disadvantage for determining soilwater contents for larger (field) scales wherein a large number of samples or measurements must be obtained to fully characterize the system, especially for heterogeneous systems. Conversely, the gas-phase partitioning tracer test provides measures of soil-water contents at larger scales. The basis of the gas-phase partitioningtracer method for measuring soil-water content was presented by Brusseau et al. (1997), and a few additional applications of the method have since been reported (Deeds et al., 1999; Kim et al., 1999; Nelson et al., 1999). The purpose of this paper is to report the results of a series of experiments conducted in a large, heavily instrumented weighing lysimeter to investigate the efficacy of the method under controlled, intermediate-scale conditions.

MATERIALS AND METHODS

The experiments were conducted in a large weighing lysimeter located at The University of Arizona's Karsten Center for

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Turfgrass Research. The lysimeter is 4.0 m deep, 2.5 m in diameter, and contains a homogeneous packing of Vinton fine sand (sandy, mixed, thermic Typic Torrifluvents) with a mean bulk density of 1.38 Mg m⁻³ and porosity of 0.47. Details regarding the lysimeter instrumentation and experiment setup may be found in Nelson et al. (1999) and Carlson (2000).

The first two experiments (1 and 2) were conducted at a volumetric soil-water content of 0.06. Following an infiltration event to increase the soil-water content to 0.15, two more experiments (3 and 4) were completed using flow rates similar to those used in the previous set. The lysimeter was then allowed to drain and a fifth experiment was conducted at a soil-water content of 0.07. Conditions for the five experiments are presented in Table 1. The flow rates were based on system constraints and what would typically be found in the field during a full-scale tracer test. Sulfur hexafluoride (SF₆) was used in all experiments as the conservative tracer while trichlorofluoromethane (CFM) was used as the bulk-water partitioning tracer for Exp. 1 to 4 and difluoromethane (DFM) was used for Exp. 5. Pertinent properties of the tracers are listed in Table 2.

The gas tracers, mixed in a balance of N, were contained in a gas cylinder and injected directly into the lysimeter. Two two-way valves were used to switch between the tracer and tracer-free gas sources. Tracer injection began once steady state gas flow was established. Following tracer injection, tracer-free air was injected to elute the tracer pulse. The volume of the tracer pulse was ≈ 40 to 45% of the total gas pore volume. To prevent drying of the porous-medium during the tracer tests, the injected air was humidified to >95% by passing it through a water tower before injection.

Samples were collected from both the influent and effluent gas streams. The gas samples were collected by withdrawing samples through a septum into a disposable needle-tipped syringe. The samples were then injected from the syringe into evacuated 80-mL aerosol canisters (Tracer Research Corp., Tucson, AZ). Syringes were used only once. The tracers were analyzed by gas chromatography using an electron capture detector (SF₆, CFM) or flame ionization detector (DFM).

The breakthrough curves for all experiments were analyzed by calculating the zeroth and first temporal moments to quantify mass recovery, travel time, and retardation, as discussed in many references (e.g., Skopp, 1984; Jin et al., 1995). Retardation factors (*R*) for the water-partitioning tracers were calculated as the quotient of the travel times for the partitioning and nonpartitioning tracers, respectively. Soil-water contents (θ_w) were calculated as: $\theta_w = (R - 1)\theta_a K_H$, where θ_a is gasphase porosity and K_H is Henry's coefficient. The soil-water contents obtained from the tracer tests were compared with values obtained using traditional methods, including gravimetric core analysis, neutron thermalization, time domain reflectometry, and conversion of soil tension. The techniques employed for these methods are discussed in Nelson et al. (1999)

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Abbreviations: θ_w = soil-water content; CFM, trichlorofluoromethane; DFM, difluoromethane; SF₆, sulfur hexafluoride.

Table 1. Experimental conditions.

Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
30.7	48.7	31.6	52.3	30.0
1.4	2.6	2.0	3.8	1.4
2.0	1.2	1.5	0.75	2.0
0.43	0.46	0.45	0.42	0.46
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and Carlson (2000). Soil-water content distributions obtained using the traditional methods show that water saturation was relatively uniform throughout the lysimeter and remained essentially constant through the course of an experiment.

RESULTS AND DISCUSSION

Breakthrough curves measured at the effluent sampling location (3.85 m from injection plane) are shown in Fig. 1 for all experiments. The breakthrough curves for SF₆ are relatively symmetrical with sharp arrival and elution fronts for all experiments, indicating ideal transport. Retention of the partitioning tracers (CFM and DFM) is indicated by the retardation exhibited by their breakthrough curves with respect to those of the conservative tracer (SF₆). Retardation factors and tracer-derived soil-water contents are reported in Table 3.

The experiments conducted at the higher soil-water content yielded higher retardation values, as expected. For the lower soil-water content experiments, the retardation factor obtained with DFM (Exp. 5, R = 1.53) is significantly larger than the values obtained using CFM (Exp. 1 and 2, R = 1.07). This difference reflects DFM's smaller $K_{\rm H}$ value and thus greater partitioning to water. Given these differences in retardation, it is likely that DFM would provide more robust estimates of soil-water content for the lower soil-water contents.

Average values of θ_w obtained from independent measurement methods for each experiment are reported in Table 4. Inspection of Tables 3 and 4 provides a comparison of tracer-derived vs. independently measured soil-water contents. The tracer-derived values are 111 and 85% of the mean of the measured values for Exp. 1 and 2, respectively, which were conducted at a lower soil-water content. For Exp. 5, which was also conducted at a lower soil-water content, the tracer-derived value is 97% of the mean of the measured values.

Table 2. Tracer properties. C_0 = input concentration; CFM = trichlorofluoromethane; DFM = difluoromethane; K_H = Henry's coefficient; SF₆ = sulfur hexafluoride.

Tracer	C ₀	K _H
	μΙ	L^{-1} —
SF ₆	50	70 †
		132‡
CFM	75	2.1§
DFM	4300	0.5

† Wilson and MacKay (1995).

‡ Olschewski et al. (1995).

§ Estimated using Henrywin v. 3.03; Meylan and Howard (1991).

¶ Measured (Costanza, 2001).

Table 3. Experiment results for tracer tests. $\theta_w = \text{soil-water content}; CFM = \text{trichlorofluoromethane}; DFM = difluoromethane.}$

Experiment	Tracer	Retardation	θ _w	
1	CFM	1.07	0.062	
2	CFM	1.06	0.052	
3	CFM	1.16	0.121	
4	CFM	1.14	0.107	
5	DFM	1.53	0.069	

The better performance obtained with DFM likely reflects its greater retardation compared with CFM, as discussed above.

For Exp. 3 and 4, which were conducted at the higher soil-water content, the tracer-derived values are 82 and 71% of the measured values, respectively. The reduced efficacy observed for these experiments may be related to advective-transport or mass-transfer constraints associated with the higher soil-water content. For example, the larger water saturation reduces the air-phase relative permeability and may decrease the continuity of the gas-phase for the higher soil-water content system. This could make it more difficult for the tracer pulse to contact the entire water phase. In addition, it is possible that the thicker water films and pendular rings associated with the higher soil-water content may cause mass transfer of the partitioning tracer between the air and water to be rate-limited by aqueous-phase diffusive constraints (e.g., Popovicová and Brusseau, 1998; Costanza and Brusseau, 2002). Theoretically, nonequilibrium conditions caused by rate-limited mass transfer do not influence the first temporal moment (travel time). Therefore, nonequilibrium conditions should not affect the calculated retardation of the partitioning tracer and the measured soil-water content. However, in practice, due to experimental constraints, rate-limited mass transfer can lead to underestimates of the first moment and therefore of the estimated soil-water content.

CONCLUSIONS

The partitioning tracer method provided reasonable estimates of soil-water content for the relatively ideal lysimeter system, compared with traditional methods, especially at the lower soil-water content. The gas-phase partitioning tracer method for the in situ determination of soil-water content has been shown to be relatively accurate and responsive to changes in soil-water content

Table 4. Independent determination of soil-water content (θ_w); TDR = time domain reflectometry.

Experiment	TDR (θ _w)	Cores (θ _w)	Tension (θ _w)	Neutron probe (θ _w)	Mean
1	0.056	0.056	_	_	0.056
2	0.060	0.062	-	-	0.061
3	0.149	_	0.148	0.148	0.148
4	0.148	_	0.150	0.152	0.150
5	0.074	-	0.069	0.071	0.071



Fig. 1. Breakthrough curves for SF₆ (sulfur hexafluoride; nonpartitioning tracer) and trichlorofluoromethane (CFM) or difluoromethane (DFM) (partitioning tracer) obtained from (A) Exp. 1, (B) Exp. 2, (C) Exp. 3, (D) Exp. 4, (E) Exp. 5.

at the intermediate scale. The gas-phase partitioning tracer test provides an averaged soil-water content of the entire swept area, which may be significantly larger $(10^{1-2}$ -m scale) than traditional methods as determined by system design. With the appropriate selection of partitioning tracers, proper implementation, and favorable subsurface characteristics, this method appears to be a

potentially viable alternative for determining soil-water content at the field scale and merits further evaluation.

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Fig. 1. Continued.

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